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Compact Digital Holscope with Dual Wavelength

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ABSTRACT

Digital holography allows fast, nondestructive, full-field 3D measurement of reflecting as well as transmitting objects. It is a well-established two-step method of digital recording and numerical reconstruction of the full complex field of wavefront. It has found applications in diverse fields, such as micro-optics and MEMS metrology, cell imaging and particle characterization. However, for quantitative phase measurement there is 2π by phase ambiguities that limit measurements of optical path lengths to the wavelength of the illumination light. For continuous profiles, phase unwrapping is used to overcome the phase jumps. One approach is to use a synthetic wavelength using two lasers with different wavelengths. This synthetic wavelength would depend on the wavelengths of the two sources and thus can be tuned by selecting appropriate sources. In this paper, this concept is integrated into the compact digital holscope which provides the system with the capability of measuring over a range of step heights from the nanometer to the micrometer realm. Applications of the system for reflecting geometries is discussed.

Keywords: Digital holography, Compact Digital Holscope, Dual wavelength, Three-dimension measurement

1. INTRODUCTION

Digital holography (DH) can achieve fast, nondestructive and full-field 3D measurement for either reflecting or transmitting objects. It is usually composed of two steps, the digital recording of hologram and numerical reconstruction of the complex amplitude of the object wavefront. The numerical reconstruction for the digital hologram presents several important advantages such as the digital propagation of the wavefront and the numerical correction of the optical system aberrations. With the development of charge coupled device (CCD) and digital image processing technology, DH has been widely used in many fields, such as micro-optics and MEMS metrology, cell imaging and particle characterization and so on[1-6].

In DH, the quantitative amplitude and phase information can be obtained by numerical reconstruction of the hologram. The phase information is mainly determined by the morphology of the reflecting samples or the thickness and refractive index of the transmission samples. However, for quantitative phase measurement, there is 2π by phase ambiguities that limit measurements of optical path lengths (OPL) to the wavelength of the illumination light. When the OPL is larger than wavelength, it can't be accurately measured. In most instances, phase unwrapping algorithms are used to retrieve the true continuous OPL map of the samples, but for high aspect-ratio samples such as specimen with steps on its surface, this approach may generate an error. In addition, phase unwrapping methods are often time-consuming and this will reduce the speed of real-time measurement.

An effective approach for high aspect-ratio samples measurement is dual wavelength digital holography, which uses a synthetic wavelength generated from two lasers with different wavelengths. This synthetic wavelength would depend on the wavelengths of the two sources and thus can be tuned by selecting appropriate sources. By choosing two closer wavelengths to produce a longer synthetic wavelength, the wavelength can be extended in the range of 2π discontinuities in the phase map. [7-11].

In this paper, dual wavelength digital holography is integrated into the compact digital holscope, which provides the system with the capability of measuring over a range of step heights from the nanometer to the micrometer realm. Applications of the system for reflecting geometries are discussed.

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2. COMPACT DIGITAL HOLOSCOPE WITH DUAL WAVELENGTH

2.1 Compact digital holoscope

The compact digital holoscope (CDH) is shown in Figure 1. The CDH is fixed on top of a five-dimensional adjustment platform with samples in the upper surface. By adjusting the platform, the distance from samples to CDH can be changed responsively.

Figure 2 shows the schematic structural view of the compact digital holoscope. Two laser sources with different wavelengths are connected with a "2 in 1" optical fiber coupler simultaneously and then come into the CDH system. A diverging laser beam from the fiber end provides the magnification in the lensless geometry. This beam is divided into two parts by using a beam splitter. One beam illuminates the samples and the other is incident on the plane mirror. The sample is illuminated by the diverging beam and the scattered light from the sample (Object beam) is combined with the other diverging beam reflected from the mirror (Reference beam). The interference pattern is recorded by the CCD. The distance between samples and CCD or fiber end controls the magnification of the system[12,13].

Figure 1. The compact digital holoscope

Figure 2. The schematic structural view of the compact digital holoscope

The compact digital holoscope setup presents a lensless reflection microscopic geometry by using a very simple and compact optical geometry. It is very suited for study of micro-size objects with highly specular surface. The magnification of CDH is from 1 to 4 times by adjusting the distance from fiber end to samples.

2.2 Dual wavelength digital holography

In dual wavelength digital holography, two individual holograms need to be recorded by using different wavelength. Let's assume that the intensity of digital hologram recorded by CCD for wavelength λ_i ($i=1, 2$) is

$$\begin{aligned} I_i(x, y) &= |O_i(x, y) + R_i(x, y)|^2 \\ &= |O_i|^2 + |R_i|^2 + R_i O_i^* + O_i R_i^* \end{aligned} \quad (1)$$

where O_i and R_i are the object beam and reference beam for wavelength λ_i , respectively. In above formula, the first two terms are the zero order of the diffraction. The third and fourth terms form the real and virtual images, respectively. In the Fourier transform domain, the zero order and virtual images can be easily removed by spectrum filtering and the retained terms $R_i O_i^*$ can be numerical reconstructed by inverse Fourier transform and convolution method. The mathematical expression of the hologram reconstruction is as follows:

$$u_i = F^{-1} \left\{ F \{ R_i \cdot I_i \} \cdot \exp \left[j \frac{2\pi}{\lambda_i} d \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] \right\} \quad (2)$$

where F and F^{-1} denote Fourier transform and inverse Fourier transform operation, and u_i is the reconstructed complex amplitude of the object wavefront and d is the reconstruction distance for λ_i . Both phase and amplitude information can be extracted from u_i . Then we can get the phase Φ for the synthetic wavelength by calculating the argument of $u_1 u_2^*$, which can be expressed as:

$$\Phi = \arg(u_1 u_2^*) = 2\pi x \left(\frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \right) = 2\pi \frac{x}{\Lambda} \quad (3)$$

where x is the optical path lengths and Λ is the synthetic wavelength defined as

$$\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \quad (4)$$

This synthetic wavelength depends on the wavelengths of two laser sources and thus can be adjusted by selecting appropriate sources. If the difference $|\lambda_2 - \lambda_1|$ is smaller, the synthetic wavelength Λ is larger. For example, for wavelength 638nm and 660nm, the synthetic wavelength Λ is 19.14 μ m. When the OPL in measurement is shorter than 19.14 μ m, there will not be phase ambiguities, so it can resolve much higher structures in the range of synthetic wavelength. This is equivalent to expand the measurement range of digital holography for step heights from the nanometer to the micrometer realm.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

In the experiment, two fiber-coupled output diode lasers with wavelength $\lambda_1=638$ nm and $\lambda_2=660$ nm are used in the CDH system. Thus, according to Formula 4, the synthetic wavelength is 19140nm, which is far greater than λ_1 or λ_2 . The sample is a small plastic sheet with microstructure on the surface, which is like a children's slide with platform and groove. As shown in Figure 2, the fiber coupler is switched to let the beam of laser 1 or laser 2 pass through. The object beam reflected from the samples interferes with the reference beam on the CCD target. Then two digital holograms with different wavelength are recorded, respectively.

One of the digital hologram recorded by the CDH system is shown in Figure 3(a). Here the laser wavelength λ_2 is 660nm and the distance between samples and CCD is 5cm. Then the magnification of the CDH system can be calculated which is about 1.97. The hologram is reconstructed by using convolution method and the intensity of the reconstructed holographic image is shown in Figure 3(b). Figure 3(c) shows the wrapped phase map of the complex amplitude of the reconstructed wavefront. In the center of the image is the microstructure. The wrapped phase fringes are very clear along the "groove" and the phase on the "platform" is almost same. In fact, the actual height of the "platform" is about

2100nm. From the phase map in Figure 3(c), we can't determine the "platform" height. In the reflection mode, even for height steps with half wavelength jumps, the phase unwrapping algorithms can't be used to obtain the accurate phase information of the wavefront. The wrapped phase map of the reconstructed complex wavefront for wavelength $\lambda_1=638\text{nm}$ is shown in Figure 3(d). The wrapped phase fringes period is smaller than that in Figure 3(c) because of the smaller wavelength.

Figure 3. Hologram reconstruction results. (a)Digital hologram with $\lambda_2=660\text{nm}$; (b)Intensity image; (c)Wrapped phase map of (a); (d)Wrapped phase map for hologram with $\lambda_1=638\text{nm}$.

In order to compare the step height obtained with different methods, we carried out phase unwrapping operation to the wrapped phase map in Figure 3(c). The 2D and 3D unwrapped phase distribution is shown in Figure 4(a) and (b), respectively. From the color phase map shown in Figure 4, we can see the microstructure very clearly.

Figure 4. Unwrapped phase map of Figure 3(d). (a)2D distribution; (b)3D distribution.

The profiles of the microstructure along the solid and dash lines are shown in Figure 5(a) and (d), respectively. As is shown in Figure 5(a), the step height of the “platform” is about 2100nm, which is larger than wavelength $\lambda_2=660\text{nm}$. But here it's a special case for the wrapped phase map. Because the continuous wrapped phase fringes along the “groove”, we can obtain the right phase value of the “platform” with phase unwrapping operation. For a separate step higher than half wavelength, phase unwrapping algorithm will not work.

Figure 5. Profile of the microstructure in Figure 4(a). (a) along the solid line; (b) along the dash line.

Dual wavelength method is used here for the microstructure measurement. Complex amplitude of the object wavefront u_1 and u_2 are reconstructed according to Formula 2 and the phase Φ for the synthetic wavelength are calculated by using Formula 3. The wrapped phase map of the synthetic wavelength is shown in Figure 6(a). Because of the microstructure height is lower than synthetic wavelength, there are no wrapped phase fringes in the map. Figure 6(b) shows the profile of the phase along the solid line in Figure 6(a). The phase difference resulted by the “platform” height is about 1.42 and its corresponding height is 2163nm. This result is consistent well with the result shown in Figure 5.

By using dual wavelength method, the synthetic wavelength is much larger than any single wavelength and this extends the capability of measuring step heights. At the same time, the measurement error becomes larger and the accuracy of measurement decreases along the expansion of synthetic wavelength.

Figure 6. (a) Wrapped phase map by using dual wavelength method; (b) Profile of phase along the solid line in (a).

4. CONCLUSIONS

In this paper, dual wavelength method is integrated into the compact digital hologscope, which provides the system with the measurement capability for step heights from the nanometer to the micrometer range. Applications of the system for measuring reflecting microstructure are discussed.

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